Sandstone Petrology

Sand-sized grains (0.0625 to 2 mm diameter)

If present, matrix would be finer-grained (mud)

Grains comprise **at least 50%** of the unit

Also known as: Arenites

Wackes when matrix rich (> 10-15%) – old term, not used anymore

Phi Units*	Size	Wentworth Size Class	Sediment/Rock Name
		Boulders	Sediment: GRAVEL
-8	256 mm		
		Cobbles	Rock RUDITES: (conglomerates, breccias)
-6	64 mm		
		Pebbles	
-2	4 mm		
		Granules	
-1	2 mm		
		Very Coarse Sand	Sediment: SAND
0	1 mm		
		Coarse Sand	Rocks: SANDSTONES (arenites, wackes)
1	1/2 mm		
		Medium Sand	
2	1/4 mm		
		Fine Sand	
3	1/8 mm		
		Very Fine Sand	
4	1/16 mm		
		Silt	Sediment: MUD
8	1/256 mm		
		Clay	Rocks: LUTITES (mudrocks)

* Udden-Wentworth Scale

Sandstone Petrology

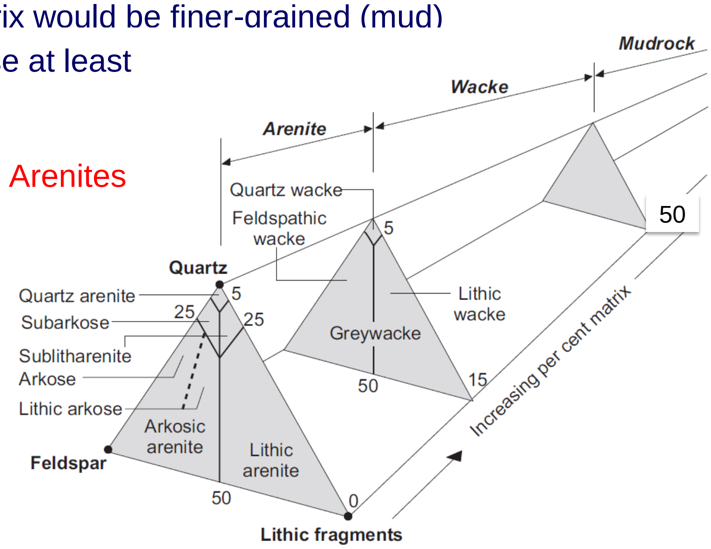
Sand-sized grains (0.0625 to 2 mm diameter)

If present, matrix would be finer-grained (mud)

Grains comprise at least 50% of the unit

Also known as: Arenites

Wackes when matrix rich (> 10-15%) – old term, not used anymore



Sandstone Petrology

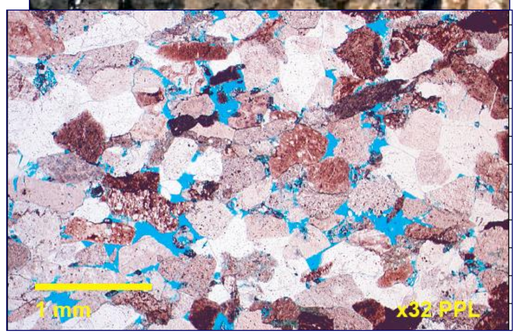
Heavily studied—Why?

Very common (order of magnitude more common than coarse clastics) ~ 20% of the rock record

Valuable source of provenance data

Paleogeographic reconstructions

Commonly contain economic resources (mineralogy/maturity very important on reservoir quality)



Sandstone Petrology

Classification Schemes

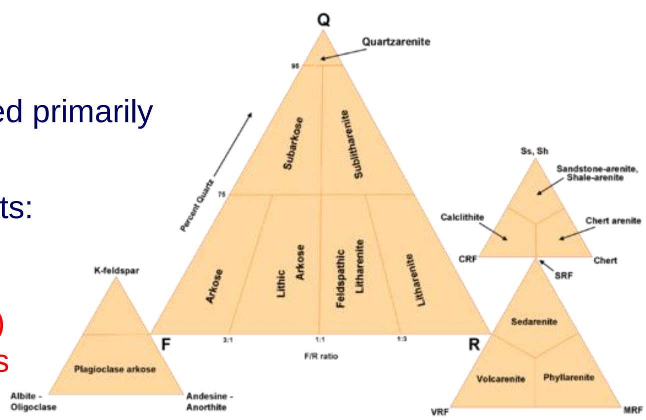
Primary texture (grain size, sorting, *etc*.) is the most fundamental aspect, but not classified by this!

Use QFL diagram

Arenites subdivided primarily by composition

3 Main components:

- Quartz
- Feldspar
- Lithic (rock) fragments



Typically accounts for >90% of rock

Folk, 1974

Quartz

Most common mineral in igneous / metamorphic / sedimentary rocks = abundantly available

Average crystalline rock **~20%** quartz

Comprise **2/3** of detrital fraction of sandstones on average

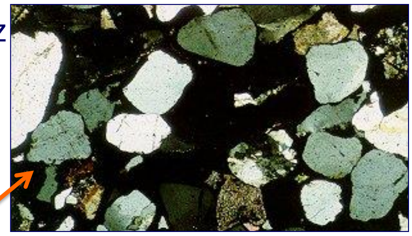
Durable: H=7, no cleavage

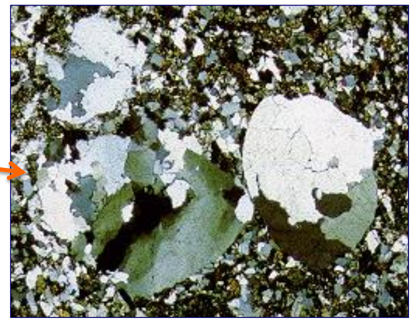
Chemically stable

Predominantly detrital grains

- Total Quartz (Qt)
- Monocrystalline (Qm): >90% a single crystal
- Polycrystalline (Qp): 2 or more crystals (both crystals > 10%)

Chert and metaquartzite are generally considered rock fragments and are not included in the Q component



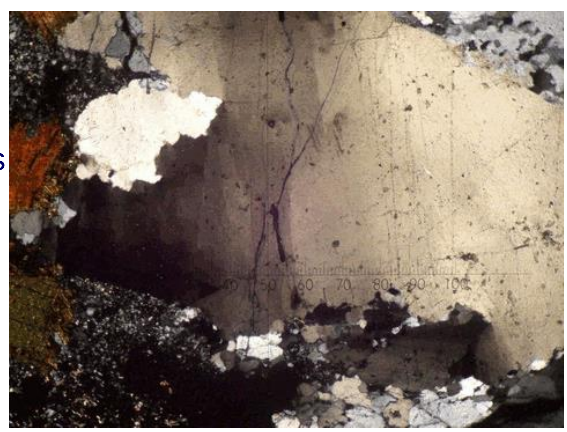


Monocrystalline Quartz

Mostly sourced from uplifted and eroded crystalline rocks

If crystals plastically deformed, will see undulatory extinction in thin section

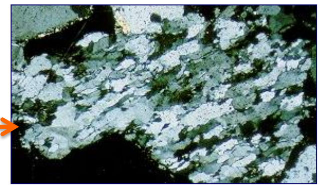
If sharp extinction under polarized light (<5° of stage rotation) suggests volcanic origin (esp. if associated with pristine [= unaltered] feldspars that are non-undulatory and/or show compositional zoning)



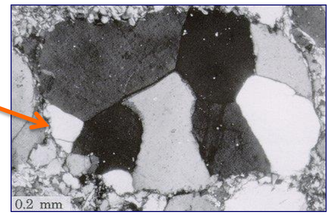
Polycrystalline (Composite) Quartz

May show several types of internal structure:

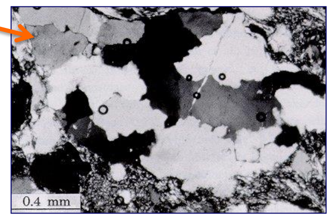
Elongate structure: commonly stretched by metamorphic processes; generally associated with recrystallization (cf. mylonites, *etc.*)



Grain packing: optimal grain boundaries at 120° = **thermally induced recrystallization**



Grain size: for any given grain size, greater numbers of small crystals = more likely metamorphic (meta-pelites…); fewer, possibly igneous. This is particularly true for finer grain sizes!



Sutures: Straight more likely igneous. Undulatory more likely metamorphic.

Feldspars

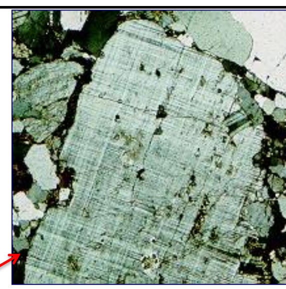
Most abundant mineral group in crust: **60%** of mineral grains in crystalline rock

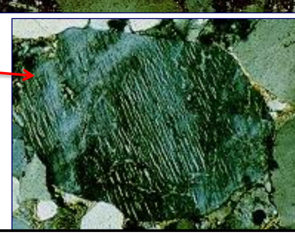
Occurs **3:1** (feldspar:quartz) in crystalline rocks, but is only **1:6 in sandstones**! (18x reduction due to weathering and erosion/attrition)

Average sandstone: ~10-15% feldspar

Typically divided into 3 groups:

- Potassium Feldspar
- Plagioclase
- Microperthite





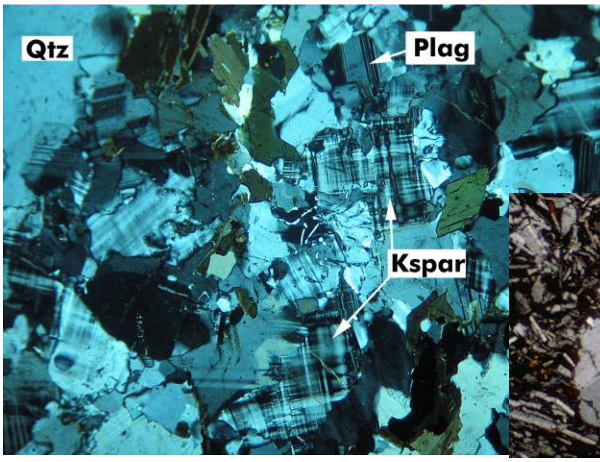
Commonly serves as a distinctive indicator of provenance rock

Potassium Feldspar

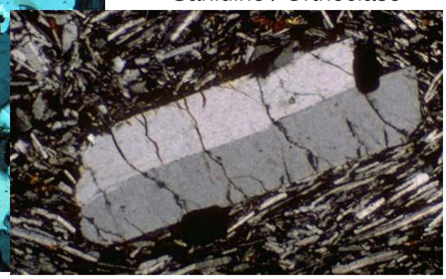
Potassium Feldspar: includes orthoclase, microcline, sanidine

ID by Carlsbad twins or cross-hatch twinning under XPL

Microcline



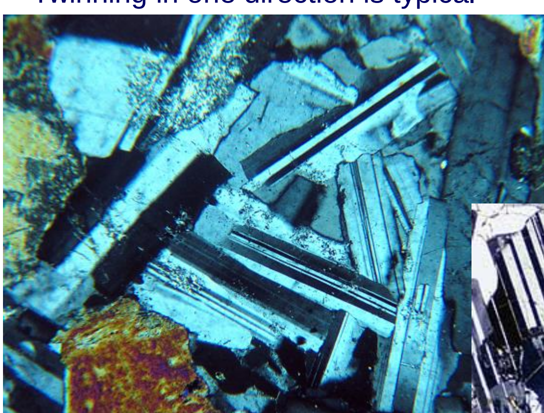
Sanidine / Orthoclase

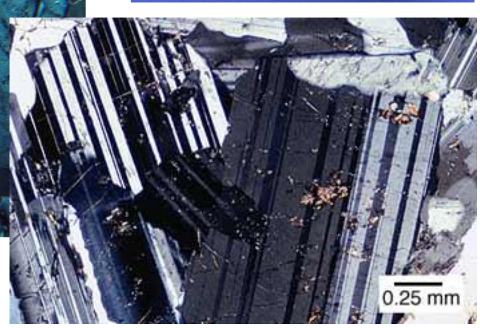


Plagioclase Feldspar

Plagioclase: ranges from albite (Na-rich) through to anorthite (Ca-rich)

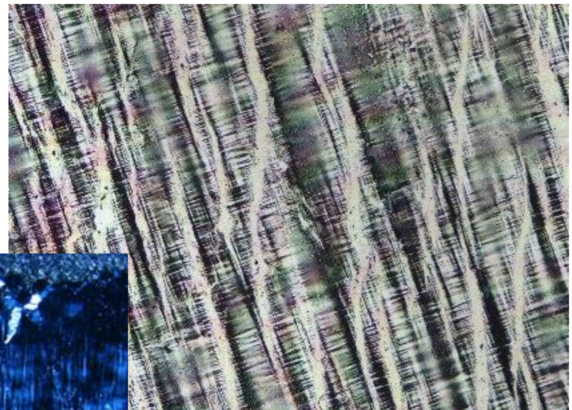
Twinning in one direction is typical

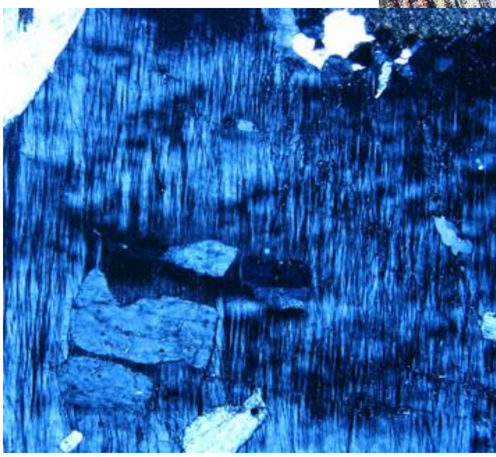




Microperthite

Microperthite: intergrowth of Na/K feldspar





Broad lamellae of plagioclase traversing tartan twinning of potassium feldspar

Feldspars

Can be difficult to ID grain types in thin section, esp. if grains too small for optic axis figures

Look for twinning of crystals

Staining methods commonly help (K and Ca) to differentiate Plag and K-spar

SEM may be employed to help ID types

Feldspars

Chemical alteration (diagenesis):

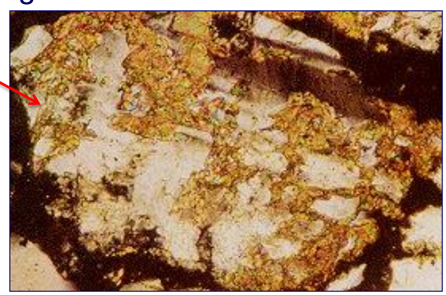
Illitization: K-spar often converted *in situ via* water percolation

Kaolinitization: Chemical transformation of feldspar (all types, but esp. K-spar)

Montmorillonitization: Like illite replacement, but in plagioclase

Calcite replacement of Plagioclase

Alteration largely post-depositional, so not diagnostic of paleoclimatic conditions



Feldspar Alteration Products

- Illite: non-expanding alumino-silicate, clay-sized, micaceous mineral $(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$
- Kaolinite: clay mineral with low shrinking-swelling capacity $Al_2Si_2O_5(OH)_4$
- Montmorillinite: swelling clay, part of the smectite group of clays $Na_{0.2}Ca_{0.1}Al_2Si_4O_{10}(OH)_2(H_2O)_{10}$

Lithic Fragments

Grains of polymineralic source rock

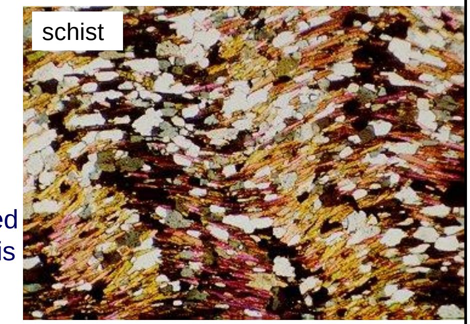
Comprise 10-20% in most sandstones

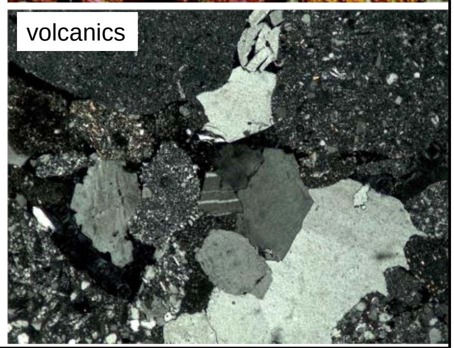
Percentages of lithics have been used heavily to interpret tectonic setting

Clasts commonly deformed and/or altered during burial, compaction, and diagenesis

Clast types dependent on:

1. Areal abundance in drainage area
2. Location in hinterland (distance to source)
3. Resistance to weathering (chemical and physical)
4. Crystal/grain sizes within the lithic fragments (rock recognizable after weathering): large crystals need large grains sizes



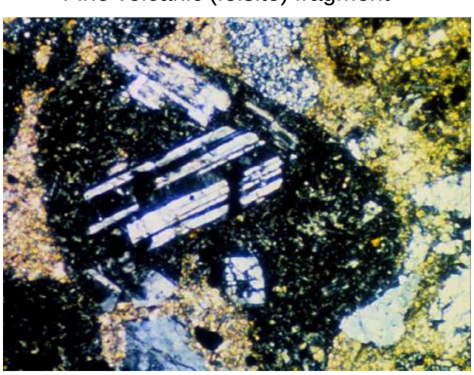


Lithic Fragments: VF

Fine volcanic (felsite) fragments are *commonly silicified* and *difficult to differentiate from detrital chert*. Ways to distinguish them:

1. Felsite contains feldspar crystals; chert is all SiO_2

Fine volcanic (felsite) fragment



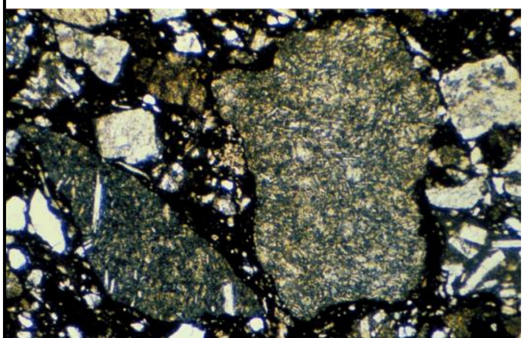
Chert

Lithic Fragments: VF

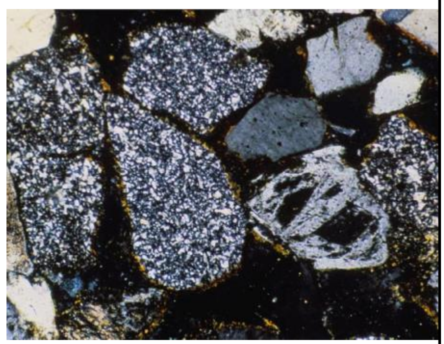
Fine volcanic (felsite) fragments are commonly silicified, and difficult to differentiate from detrital chert:

2. Presence of lath-shaped crystals; chert crystals are equant

Fine volcanic (felsite) fragment



Chert

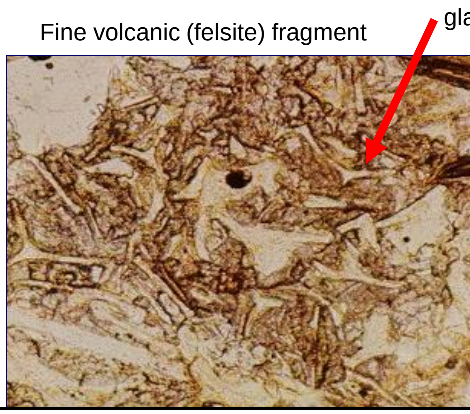


Lithic Fragments: VF

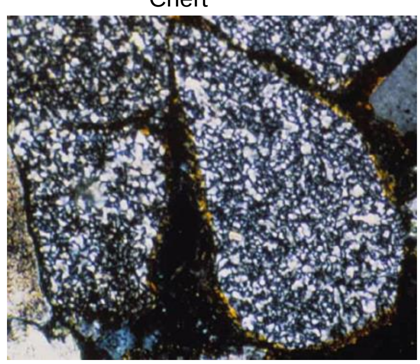
Fine volcanic (felsite) fragments are commonly silicified, and difficult to differentiate from detrital chert:

3. Grain relief in felsite more pronounced (feldspar *vs*. quartz)
4. **Felsite can have isotropic glass shards; chert does not**
5. Staining can detect feldspar (Ca or K ions)

Fine volcanic (felsite) fragment



Chert



Lithic Fragments: VF

Fine volcanic (felsite) fragments are commonly silicified, and difficult to differentiate from detrital chert:

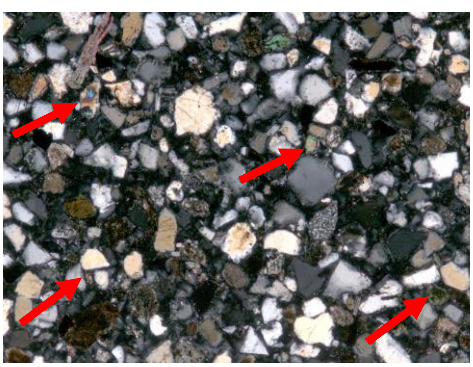
6. Chert (below) is commonly a silicified limestone: look for evidence of fossil material in PPL (*e.g.*, sponge spicules, shell fragments, *etc*.)

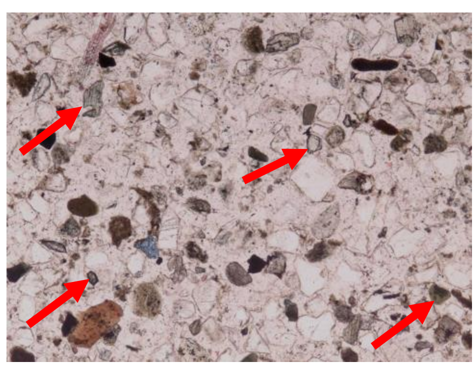
Accessory Minerals

Detrital minerals present in a rock in small amounts, but not considered essential in the naming of the rock. Includes all detrital minerals except quartz and feldspar (rock fragments are not minerals).

Mostly comprise **heavy minerals (high birefringence**). Many workers do not include micas (not bedload), but *we* will!!

Typically only constitutes **1-2% of sandstone.**





Accessory Minerals

Heavy Mineral Content — dependent on:

1. Their abundance in the source rock.

2. Survival potential of grain type (its mechanical and chemical durability).

3. Specific gravity (density) of grains (3.0–5.2 for “heavy” minerals vs. 2.65 for quartz and feldspar). As a result, they also result in finer grain sizes than the surrounding sand (***hydraulic equivalence***).

Generally more common with metamorphic source rocks (greater diversity of minerals over a broad P/T range).

Most common minerals form in both igneous and metamorphic rocks, plus have common colour variations.

Accessory Minerals

Detrital Heavy Minerals . . .

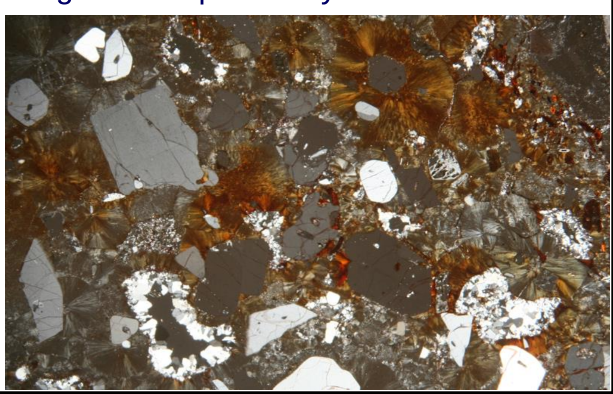
Two main ‘groups’: **Opaque** (oxides and sulphides, commonly iron) & **Non-opaque** (huge variety)

Opaques:

Generally require reflected light.

Commonly broken out using a 3-component system:

FeO (ferric iron)
Fe_2O_3 (ferrous iron)
TiO_2 (titanium)



Accessory Minerals

Detrital Heavy Minerals . . .

Two main 'groups': **Opaque** (oxides and sulphides, commonly iron based). **Non-opaque** (huge variety).

Non-Opaques:

Most common in mature sandstones are ultra-stable (ZTR index): % of ZTR relative to other non-opaque Heavy Minerals

zircon

tourmaline

rutile

Rutile with quartz

Accessory Minerals

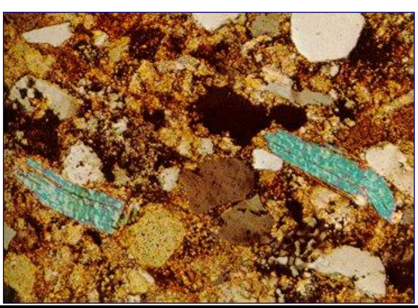
Non-Opaque Heavy Minerals

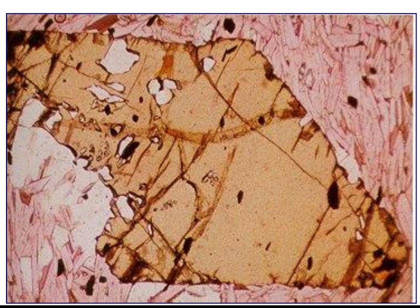
ZTR index used to assess mineralogic maturity; higher indices reflects greater maturity.

Index is the ratio of the combination of ZTR accessories relative to the remaining transparent (non-opaque) heavy minerals.

Muscovite, biotite, and phlogopite may exist (though rarely in abundance), associated with metamorphic rock types or felsic intrusives.

Biotite/phlogopite commonly break down into authigenic chlorite during shallow burial.





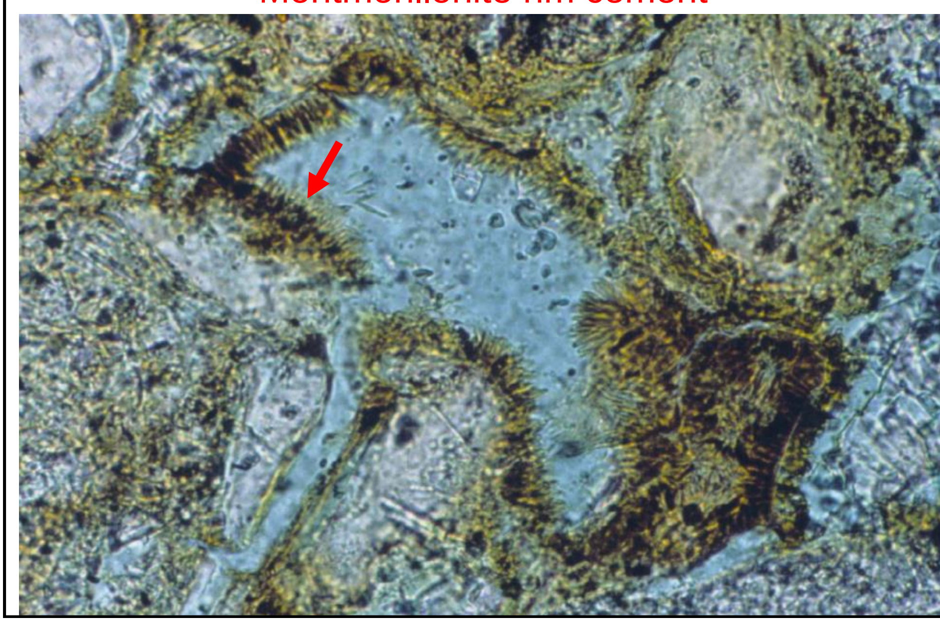
Authigenic Minerals

Grow *in situ* after deposition or during burial (diagenesis)

- Fill pore spaces
- Replace unstable framework grains and rock fragments
- Typically smaller than framework grains
- Show euhedral grain / crystal boundaries
- Cross-cutting fabrics over detrital grains
- Commonly line voids with “rim cements”

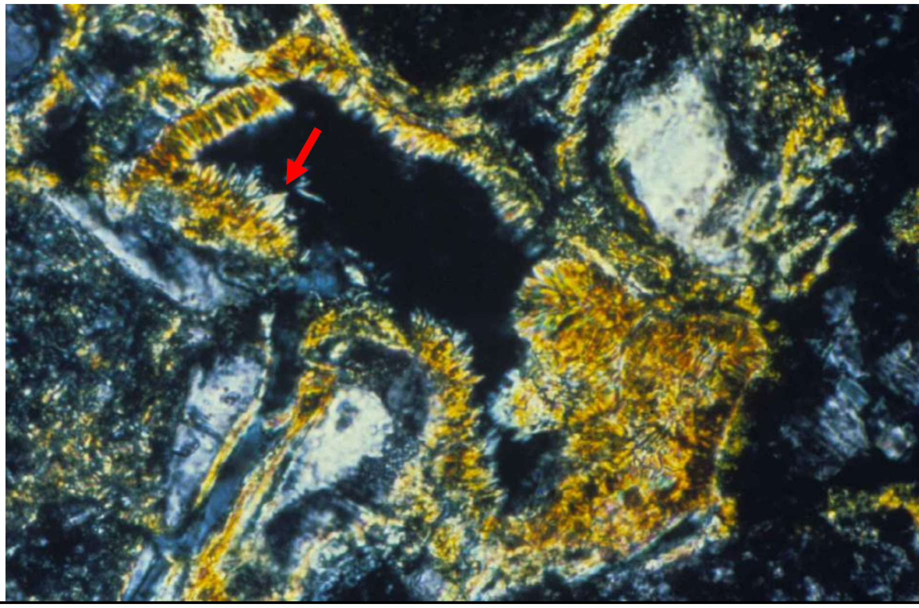
Authigenic Minerals

Montmorillonite rim cement



Authigenic Minerals

Montmorillonite rim cement



Authigenic Minerals

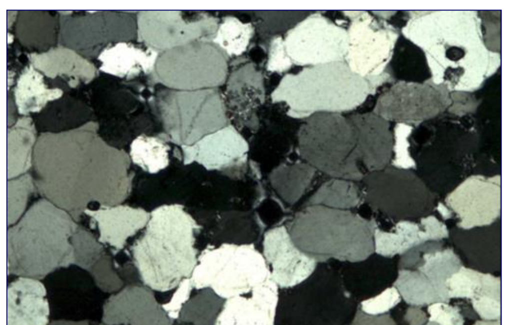
Silica

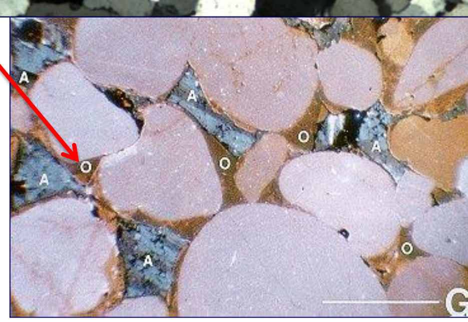
Very common cement types

Syntaxial overgrowths on grains (highlighted by “dust rims”)

Euhedral grain / crystal boundaries (may see hexagonal crystal form)

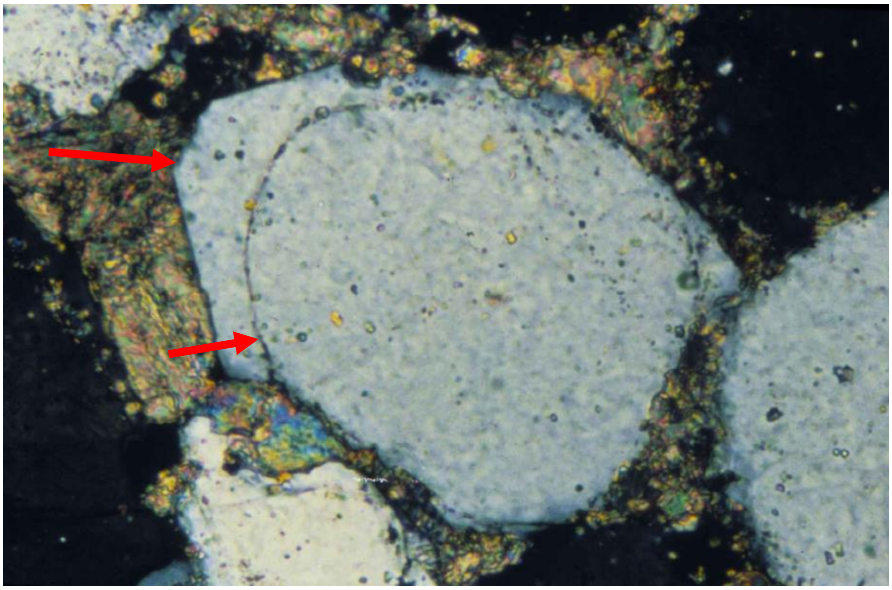
Includes chert, chalcedony, opal





Authigenic Minerals

Silica – Euhedral Quartz overgrowth



Authigenic Minerals

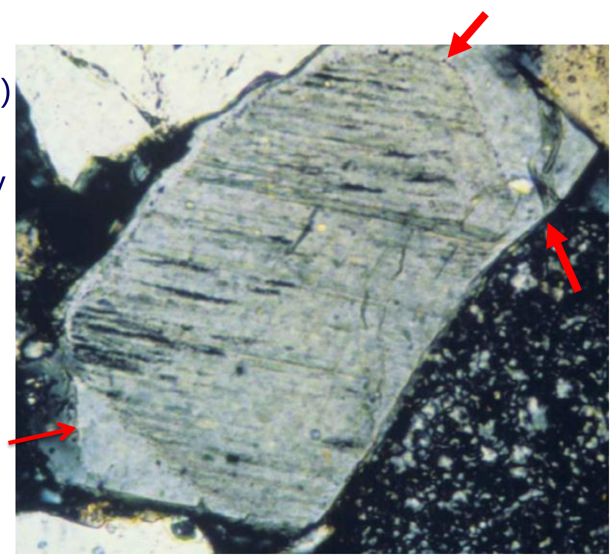
Feldspar

Much less common (deep burial conditions)

Sub-silt size commonly

Very euhedral crystals, typically untwinned

May occur as syntaxial overgrowths on detrital feldspars



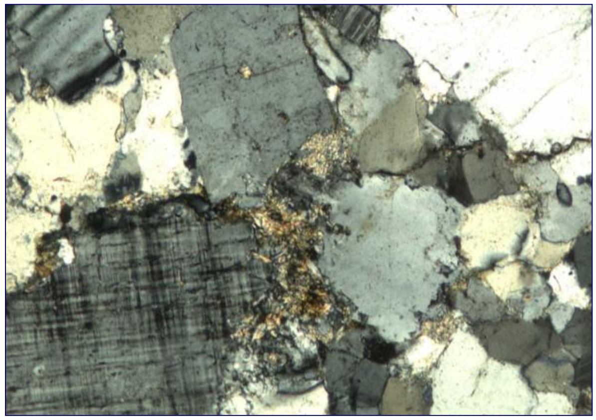
Authigenic Minerals

Clay and Mica

Many form due to detrital clay alteration during burial

Includes: Sericite (white mica), muscovite, biotite, chlorite, illite

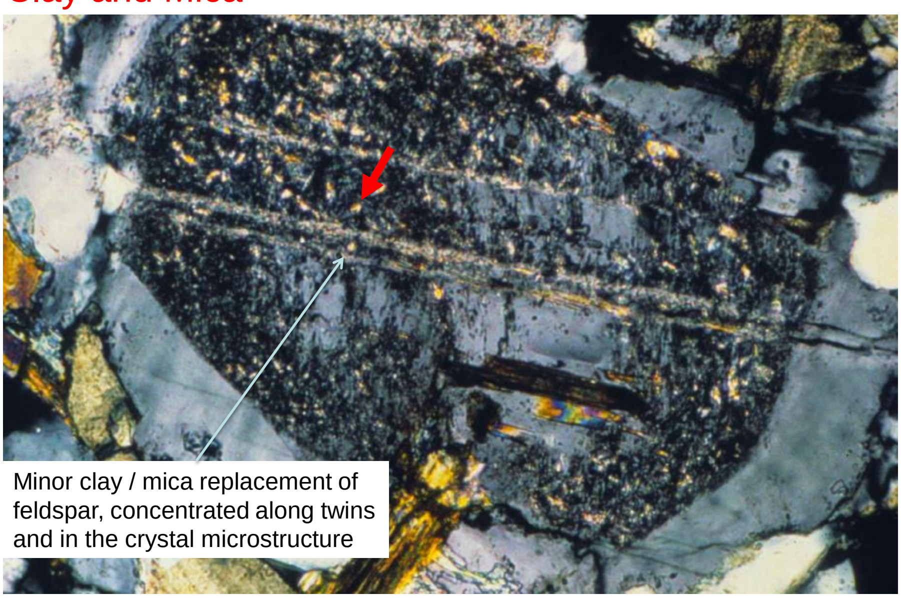
Also from feldspar and Volcanic Rock Fragments (VRF) breakdown at/near surface conditions (*e.g.*, sericite, kaolinite, illite)



Authigenic mica differs from accessory mineral mica in that the latter form distinct clasts with sharp boundaries

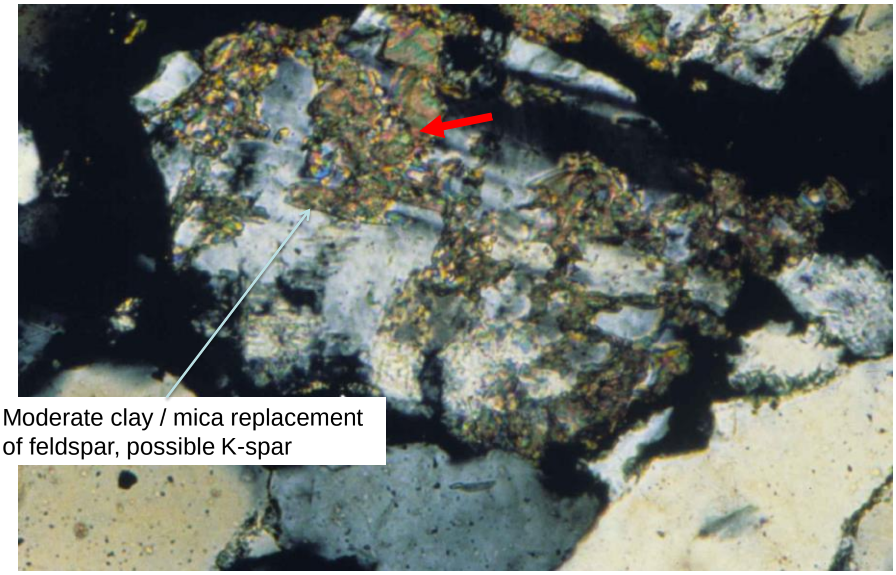
Authigenic Minerals

Clay and Mica



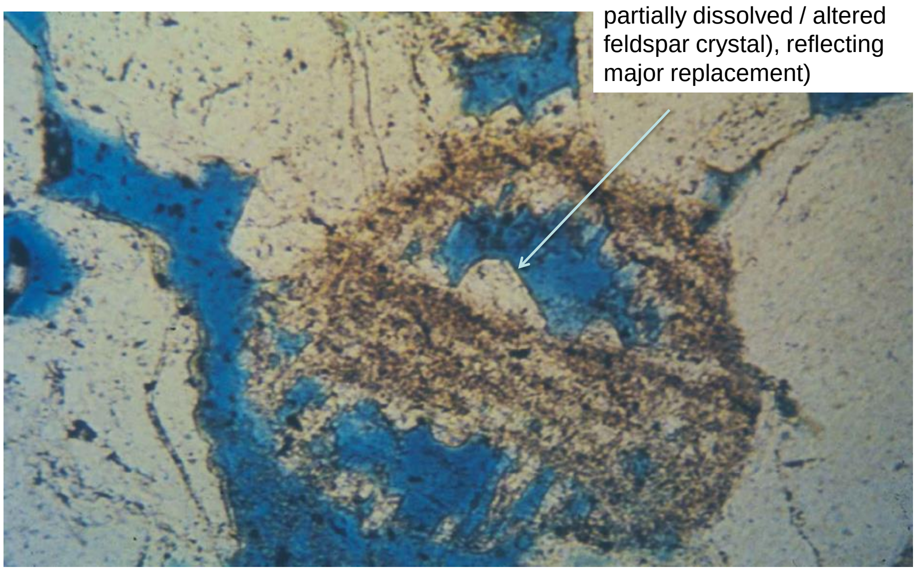
Authigenic Minerals

Clay and Mica



Authigenic Minerals

Clay and Mica



Authigenic Minerals

Glaucony – Glauconite

Iron-rich phyllosilicate (> 15% Fe_2O_3), containing variable K_2O concentrations. K is derived from sea water and retained during burial.

Bright green to rusty; darker green with higher K_2O concentrations (= highly evolved)

Largely authigenic (if detrital, may become reddish brown when oxidized)

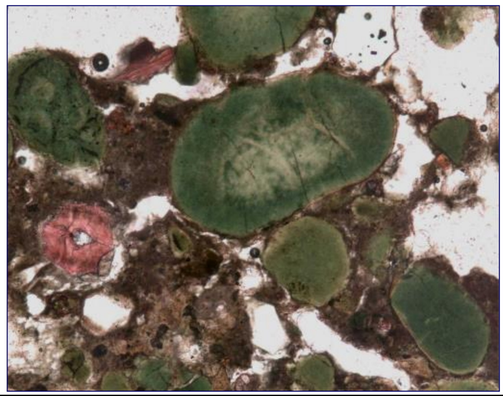
Spherical, sand-sized 'grains'

Overlapping micaceous plates

Almost exclusively marine

Commonly associated with phosphate grains/cements

Associated with sediment starvation in marine settings (omission surfaces and condensed sections) during transgressions, when most clastic sediment trapped in shallow-water settings.



Authigenic Minerals

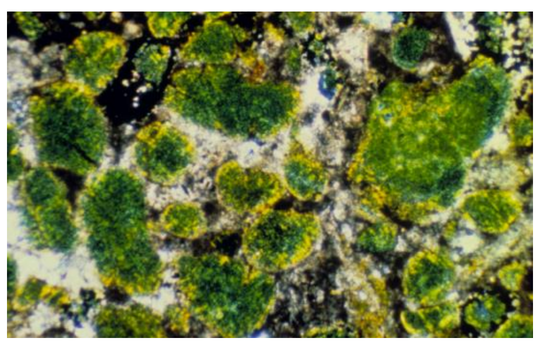
Glaucony

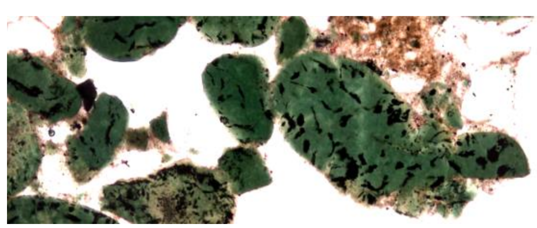
Comprises **Glauconite. Longer residence time on sea floor leads to higher K_2O.**

Characterization of facies **requires knowing that grains are autochthonous**, and haven't been transported to depositional site.

Visual observation *cannot* differentiate **glauconite** from other Fe-rich green clays: (*e.g.*, **green chlorite – Chamosite) and verdine group (***e.g.*, **Berthierine, Odinite).** One needs XRD to differentiate them!

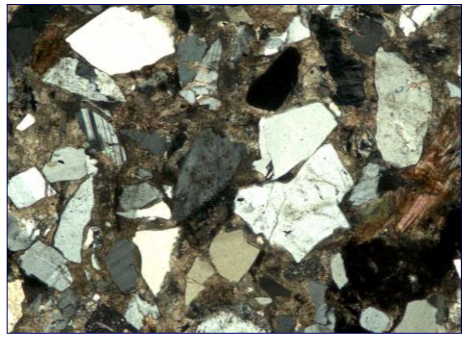
Old addage: *If its Green, its Marine*!

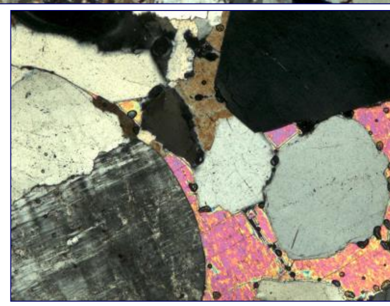




Authigenic Minerals

Cements





Carbonates (calcite, dolomite, siderite)

Iron oxides (hematite, limonite)

Sulfates (anhydrite)

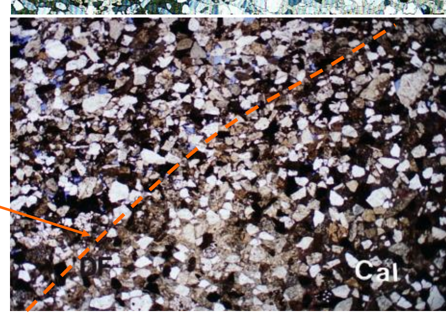
Sulfides (pyrite, marcasite)

Zeolites

Phosphates

Authigenic Minerals

Cements



Carbonates (calcite, dolomite, siderite)

Iron oxides (hematite, limonite)

Sulfates (anhydrite)

Sulfides (pyrite, marcasite)

Zeolites

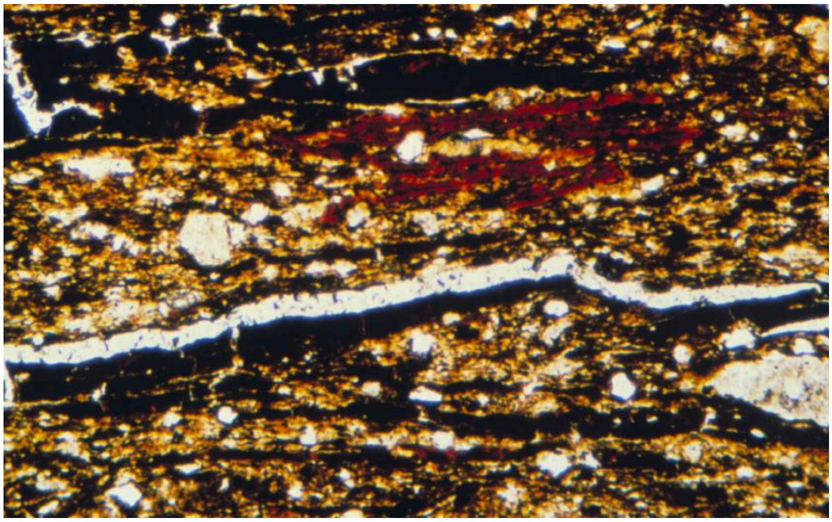
Phosphates

Diagenetic front of calcite precipitation in shaly sandstone

Other Constituents

Carbonaceous Organics (wood, coal):

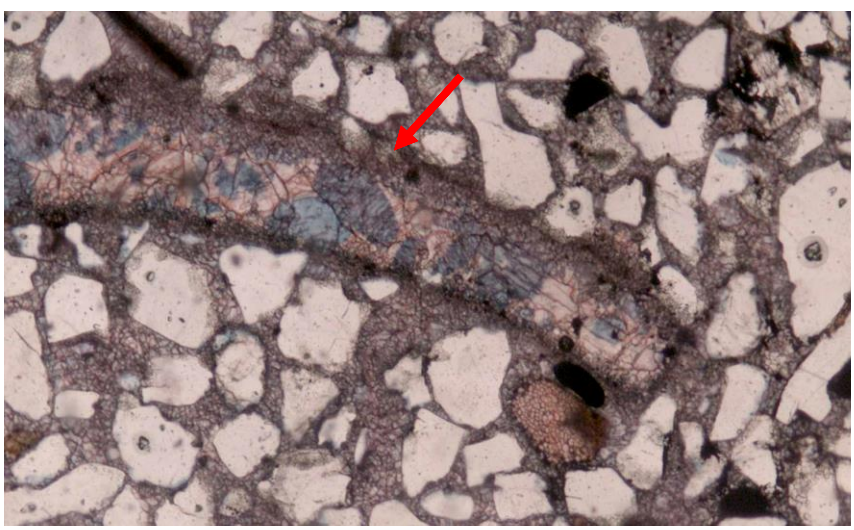
Opaque through to black and/or red fragments, generally uncommon



Other Constituents

Skeletal

Mineralized hard parts of fossils (calcite most common)



Sandstone Classification and Interpretation

Sandstone Classification

Framework *vs*. matrix = first cut-off

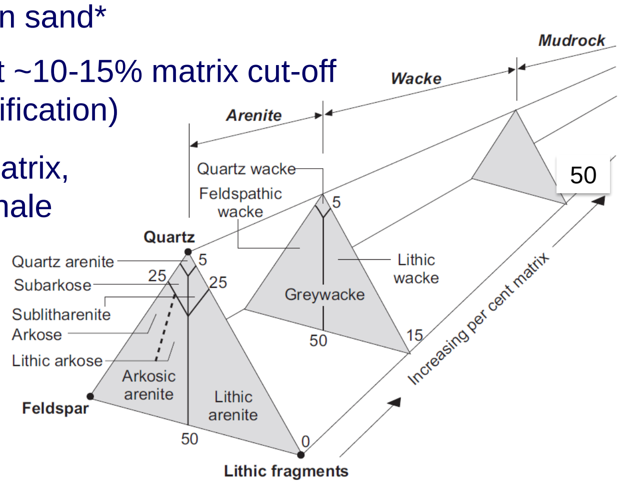
Framework: sand fraction

Matrix: smaller than sand*

Arenite *vs*. Wacke at ~10-15% matrix cut-off (depending on classification)

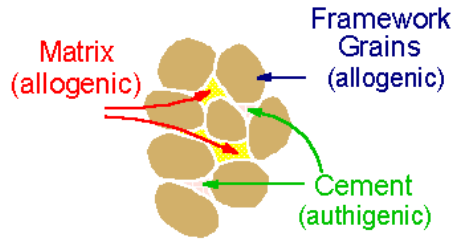
Greater than 50% matrix, sandy mudrock or shale

Note, most workers today prefer “silty sandstone” and “muddy sandstone” to “wacke”



Sandstone Classification

Framework *vs*. matrix = first cut-off
- Framework: sand fraction
- Matrix: smaller than sand*



Arenite *vs*. Wacke at ~10-15% matrix cut-off (depending on classification)

Greater than 50% matrix, sandy mudrock or shale

Matrix: original interstitial fines (a.k.a. protomatrix):
- Derived from weathering and erosion in source terrane
- Derived from weathering and erosion at depositional site

Diagenetic alteration of material to produce clay (a.k.a. pseudomatrix) is *NOT DETRITAL*.

Sandstone Classification - Schemes

Most use Q-F-L ternary diagram on framework grains

Main problem is how to deal with “quartz” (SiO_2) components

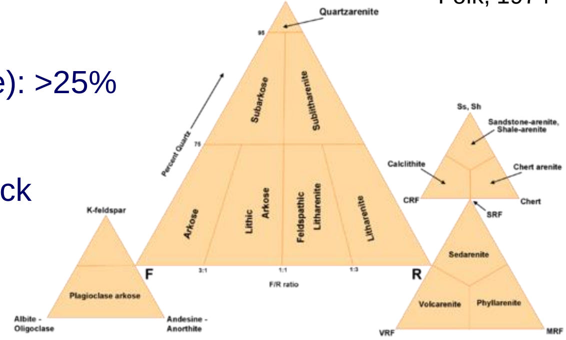
Generally rely on thin section point counts of framework grains (~400 grains)

Quartz Arenite: >95% quartz sand grains

Arkose (arkosic arenite): >25% feldspar

Lithic Arenite: >25% rock fragments

Folk, 1974



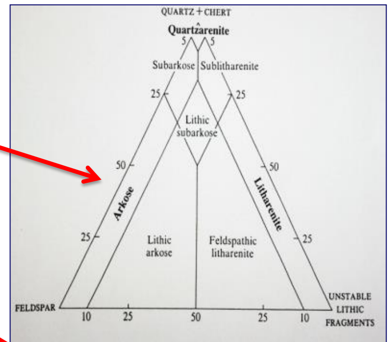
Sandstone Classification - Schemes

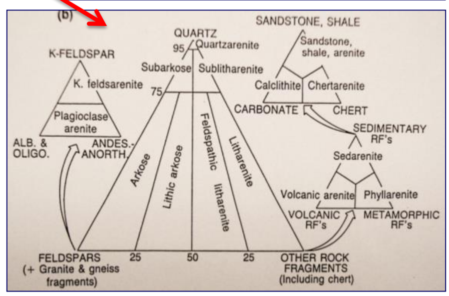
McBride (1963): Composition of framework grains only

Folk (1974): based on framework grains only as well.

Dott (1964): Sst-Wacke break at 5% matrix cutoff (very low %!)

Greywackes: 10-15% matrix-rich in clays (very immature, commonly well lithified)





Sandstone Petrology Interpretation

Describe rock

Incorporate description into interpretation of rock genesis

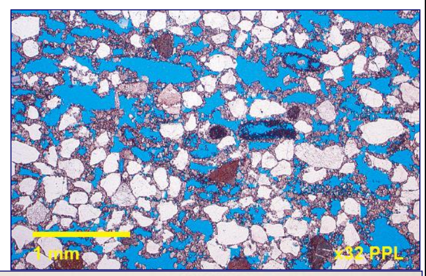
When interpreting rock, consider:

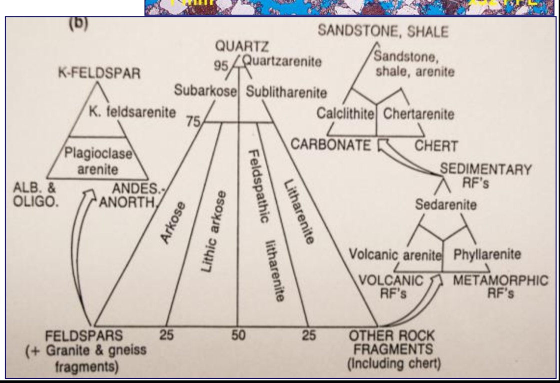
Tectonics

Climate

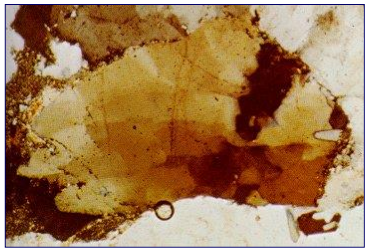
Depositional Environment

Diagenesis





Quartz as a Provenance Indicator



Granitoid Plutonics: coarse Qm (mL and coarser monocrystalline quartz)

Silicic Volcanics: angular Qm with non-sweeping extinction and vacuoles - typically volumetrically insignificant!

Metamorphic (recycled): Common Qp

Vein Quartz (Milky): generally coarse-grained Qm, indicative of crystalline bedrocks - murky with water-filled vacuoles in thin section.

Non-undulatory Qm with few inclusions are the most durable (most uniform crystal lattice) - tend to survive

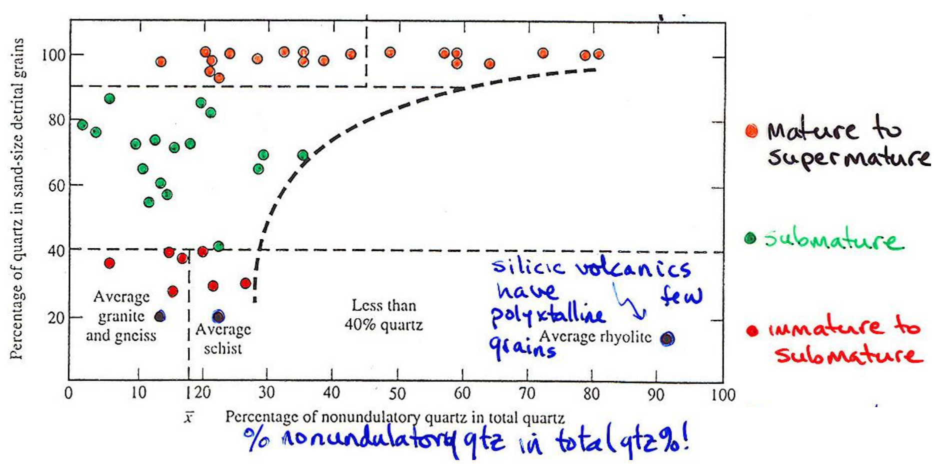
Average crystalline rock ~20% quartz

Pure quartz arenites contain <1% Qp!

Quartz as a Provenance Indicator

Non-undulatory Qm with few inclusions (most uniform crystal lattice) = most durable

Pure quartz arenites generally <1% Qp!



Feldspar as Provenance Indicators

Generally more common in mafic igneous rocks, particularly plagioclase.

Zoning more common in intrusives.

Type and percentage depends on:

1. Source terrane geology
2. Tectonic style
3. Climate/Paleoclimate

Active tectonics (= rapid uplift) + arid to semi-arid climate: up to 50% feldspar common (v. immature)

Cratonic settings + humid climate: Very rare feldspar (broken down/reworked and altered by chemical weathering);

Recycled sediments – feldspar less common.

Feldspar as Provenance Indicators

Convergent Margins: Rapid burial of immature sandstone sourced from intermediate plutonics (diorites, granodiorites) – may be plagioclase-rich

Rifted / Intracratonic terranes: K-spar-rich, compared to plagioclase (granitoid sources)

Feldspars are more prone to physical and chemical degradation (compared to quartz): Feldspars commonly occur as a finer grain size than the quartz fraction for any given sand size.

1. Larger grain surface area per unit mass results in more rapid chemical breakdown.

2. Presence of cleavage and twin planes hasten chemical alteration and also means that grains are less mechanically durable.

Feldspars are exceedingly uncommon in the silt-sized fraction and generally absent from clay sized fraction.

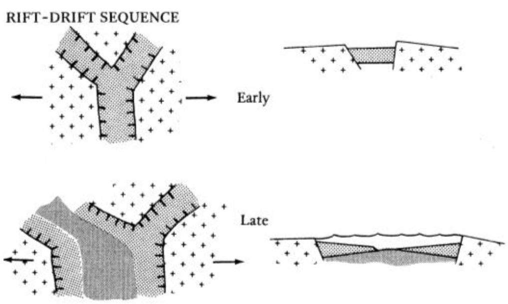
Sandstone Interpretation - Tectonics

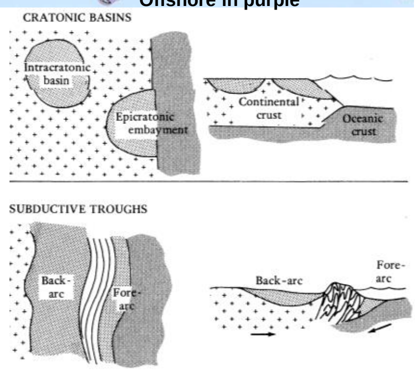
Tectonic Controls:

Type(s) of rocks exposed at surface in source area

Basin geometry, gradients, and fill patterns

Local climate (rain-shadows, *etc*…)

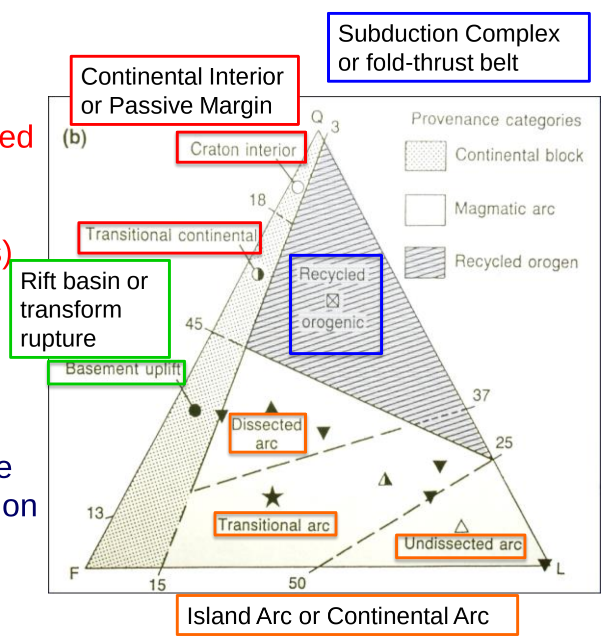




Tectonics

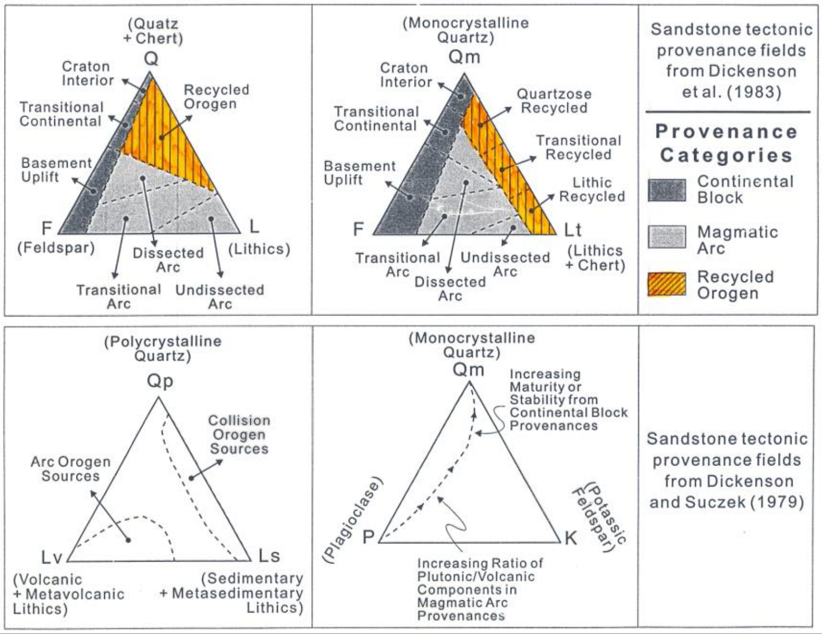
QFL plots heavily utilized to interpret tectonic setting of provenance (a.k.a., Dickinson plots)

Many trends valid, but don't blindly interpret based on what 'field' a sample lies in on a published diagram (use your insight and common sense)



Tucker, pages 53-55

Tectonics

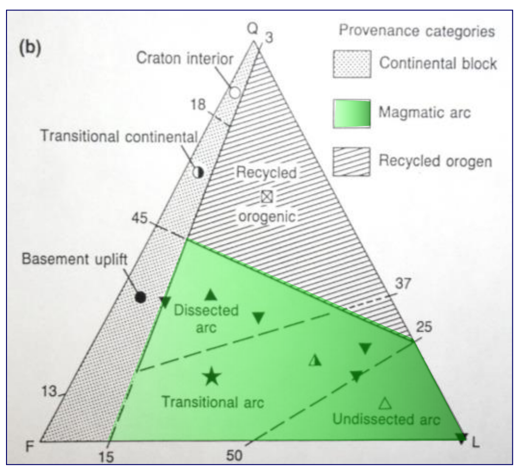


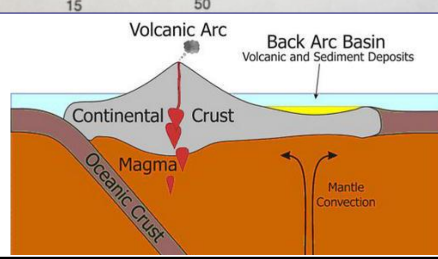
Tectonics

Magmatic Arcs

Undissected (new / undisturbed) magmatic arc: mafic volcanics + abundant plagioclase (*cf.* Jurassic, Oregon, Wash.)

Dissected (older / uplifted) magmatic arc: silicic plutons exposed; more quartz and k-spar; (*cf.* Eastern California)

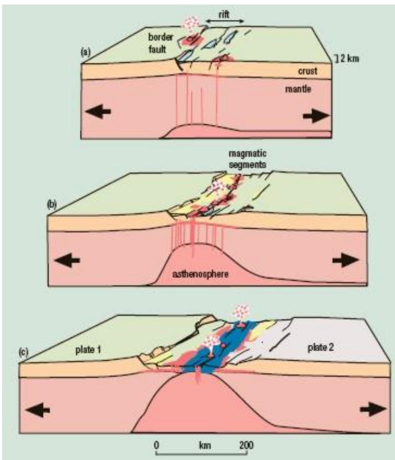


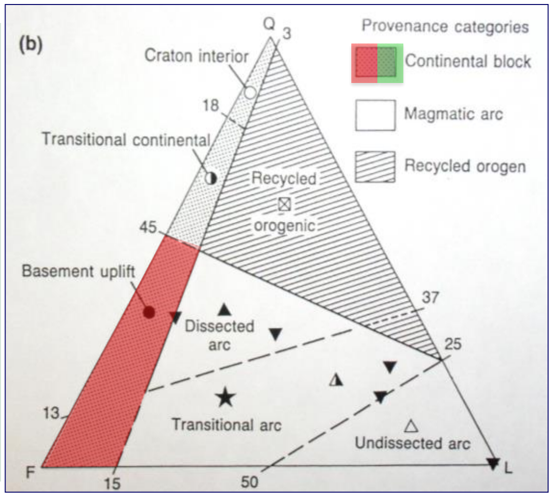


Tectonics

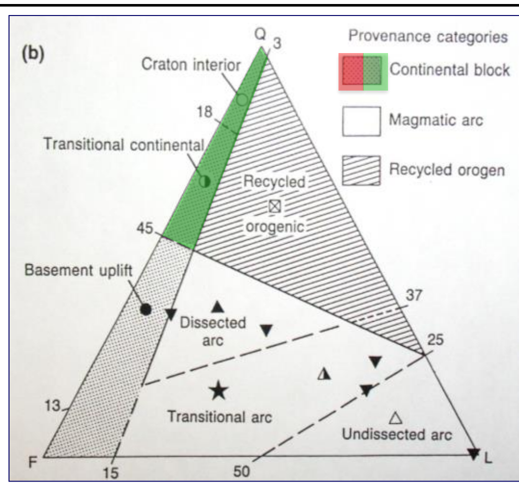
Rifted Continental

Texturally immature, rich in quartz and K-spar, localized to extensional centre (cf. Triassic of Eastern North America)

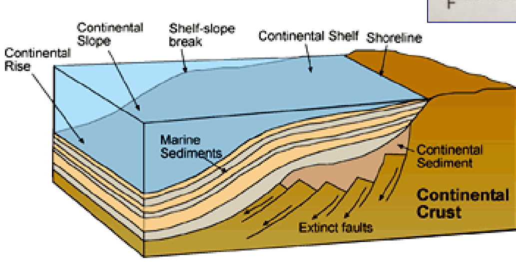




Tectonics



Passive margin: progressively fewer immature grains (quartz rich; cf. southeastern North America)

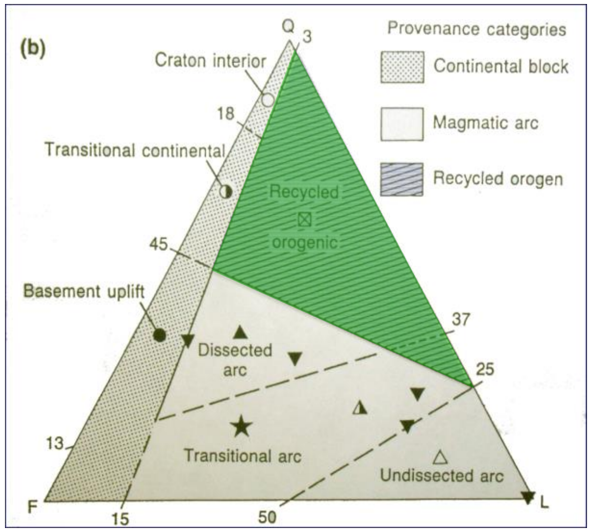


Tectonics

Collisional Zones

Oceanic: Highly deformed deep-marine sediments (common turbidites, Miocene, western North America)

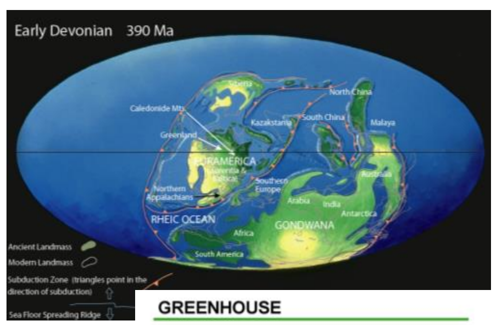
Continental Orogens: highly variable, but common reworking of sedimentary lithics (quartz-rich); (Upper Carb., Appalachians; Cret. Western Canada)



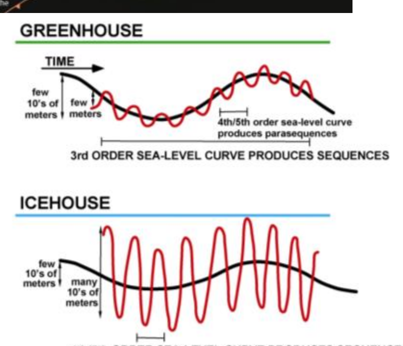
This approach often works well, but not always!

Sandstone Interpretation - Climate

Greater weathering at source = less information preserved in sediment (commonly causes far more information loss than physical transport!)



Paleolatitude estimations help to predict paleoclimate regimes



Global climate regime influences weathering (*e.g.*, greenhouse *vs.* icehouse)

Warmer + more humid = more intense weathering

Clast Lithology

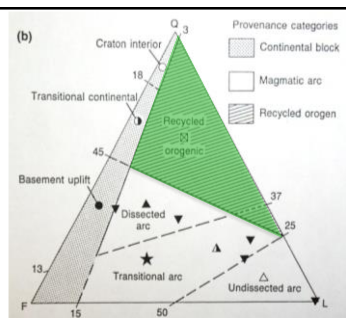
Mineral Stability: The reverse of Bowen's Reaction Series

Most stable at surface:

- Quartz, Zircon, Tourmaline, Rutile
- Chert
- Muscovite
- Microcline (K-spar)
- Orthoclase
- Plagioclase
- Hornblende, Biotite
- Pyroxene
- Olivine

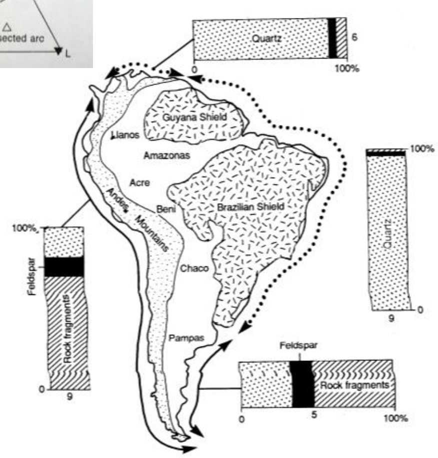
Least Stable

Climate



Comparison of semi-arid *vs.* humid fluvial sands: humid lost ~2/3 rock fragments plus most feldspars!

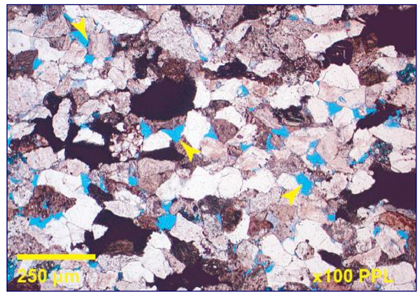
Example: Amazon regions — very humid and slow deposition with extensive weathering yields first-cycle quartz arenites! Compositionally mature but texturally immature!

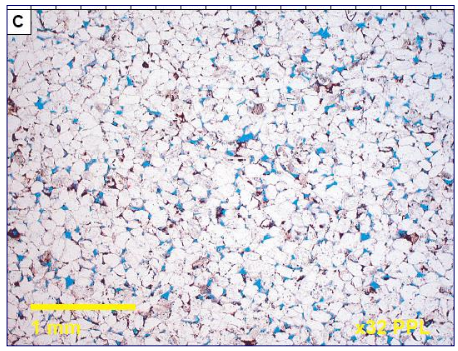


Interpreting Sandstones

Depositional Environment:

- Very difficult to quantify, but empirically deductive approach — sedimentary structures, trace fossils, fossils very important!
- Greater transport distance + higher energy conditions = better sorting and and greater textural and compositional maturity (more unstable grains destroyed)





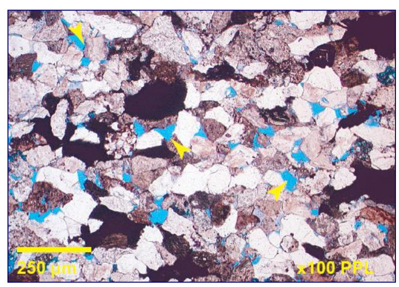
Interpreting Sandstones

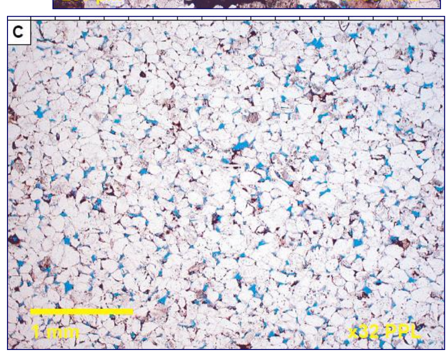
Depositional Environment:

- Significant variations in lithology expected when same sediments are subjected to extensive reworking (*cf*. fluvial sand *vs*. adjacent beach sand from same source!)

Diagenesis:

- discussed later—major impact!





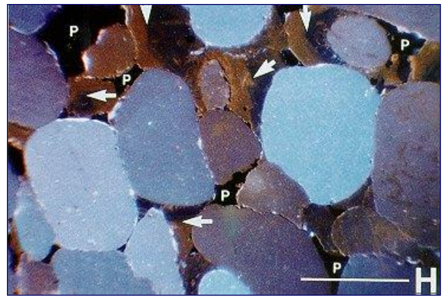
Interpreting Sandstones

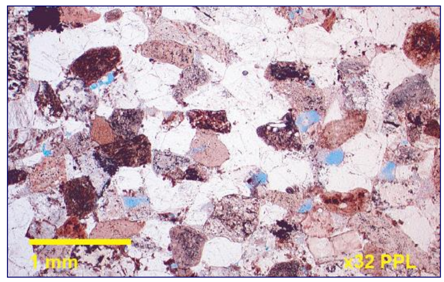
Recycled Sediment:

- Detrital sediment (and sedimentary rock fragments - chert in particular) are extremely common.

<ins>Difficult to recognize. Look for:</ins>

- Very high % quartz = suggests recycled (already mature)*
- High % non-opaque heavy minerals - mainly durable forms!
- High degree of grain rounding (textural maturity) that *accompanies* compositional maturity
- Abraded syntaxial overgrowth cements at grain margins - a clear indication of sedimentary origin!

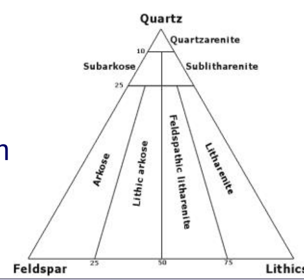


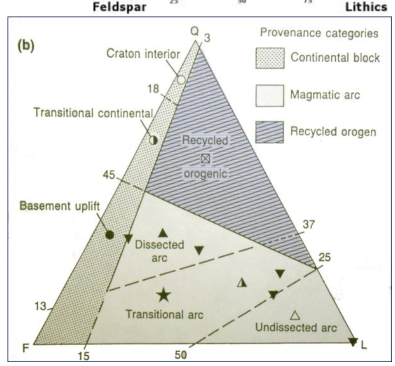


*** Climate also can do this**

Interpreting Sandstones – *e.g.*, 1

Coarse-grained sandstone composed of 95% quartz. Contains cross bedding. Grains are rounded and sub-rounded. The cross-beds are probably large-scale trough types, resulting from the migration of small dunes.

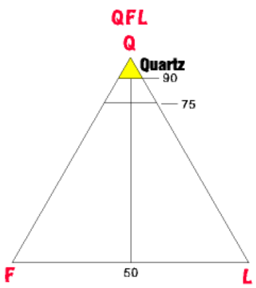


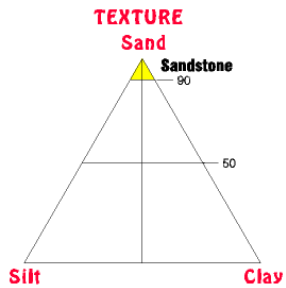


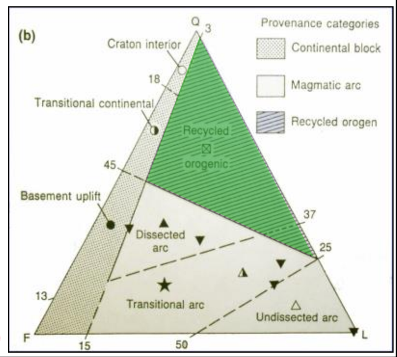
Interpreting Sandstones – *e.g.*, 1

Quartz Arenite – mature

Antietam Formation, Cambrian, Virginia. (Passive Margin source)

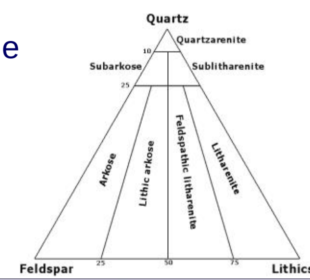


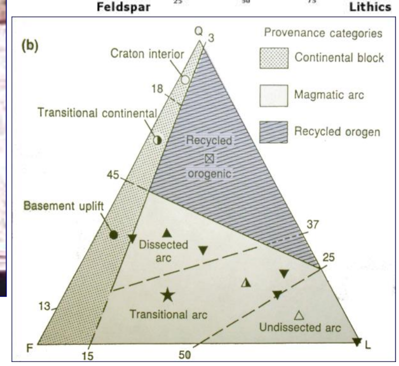




Interpreting Sandstones – *e.g.*, 2

A granule-bearing coarse-grained sandstone with a mixture of quartz and orthoclase feldspar (pink). The grains stand out in high relief in this specimen.

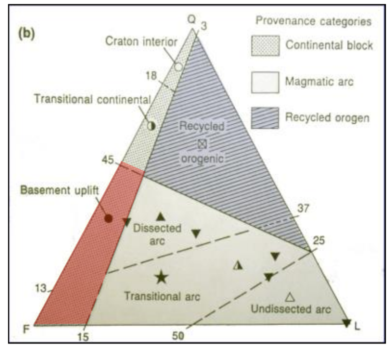


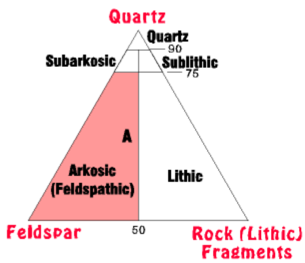


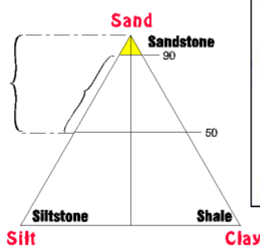
Interpreting Sandstones – *e.g.*, 2

Arkose

Likely Rift Fill. Unit from Triassic of eastern N. America

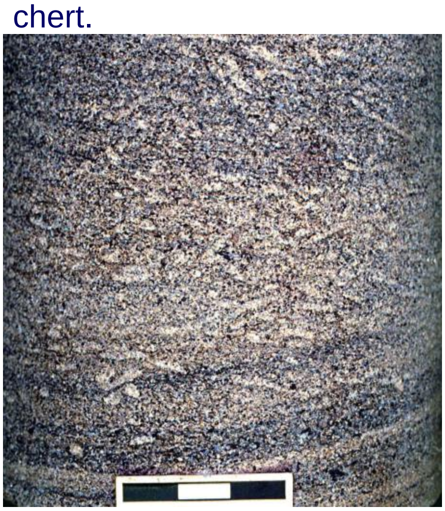


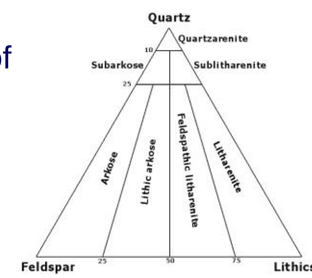


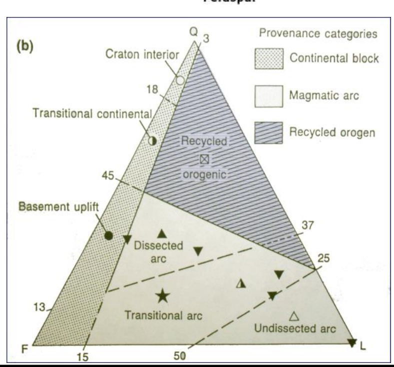


Interpreting Sandstones – *e.g.*, 3

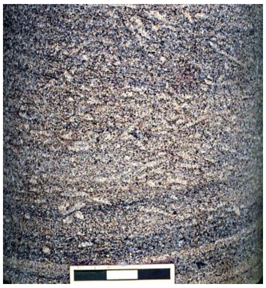
Medium-grained sandstone with dispersed coarse grains. Unit is cross-stratified and of shallow marine origin. Dark grains are chert.





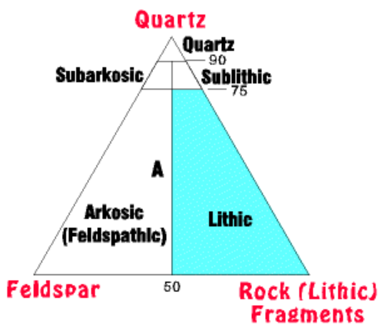


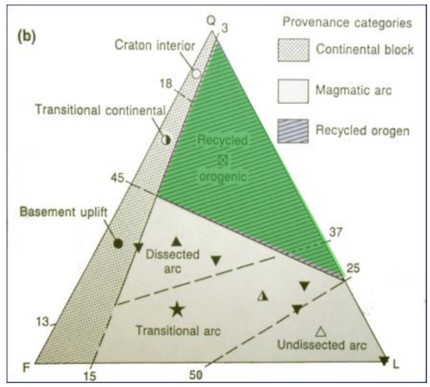
Interpreting Sandstones – *e.g.*, 3



Litharenite

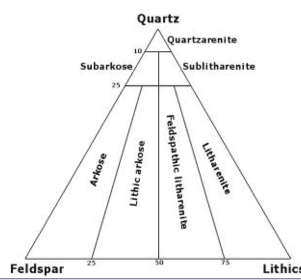
Chert derived from weathered, silicified carbonates (Cretaceous, Western Interior Seaway)

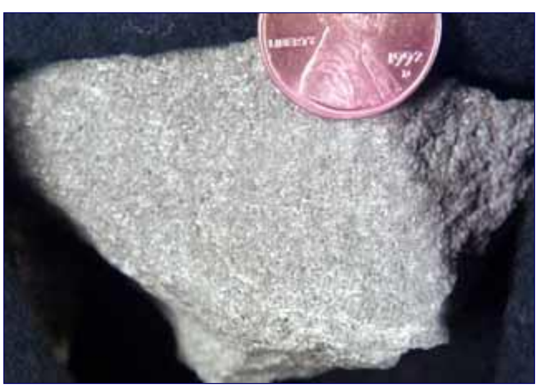


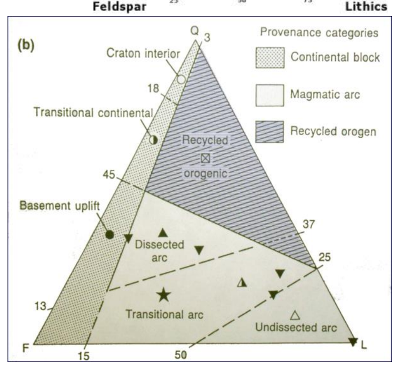


Interpreting Sandstones – *e.g.*, 4

Fine-grained muddy sandstone with 25% matrix. Clast composition: 45% feldspar, 35% quartz, 20% lithics

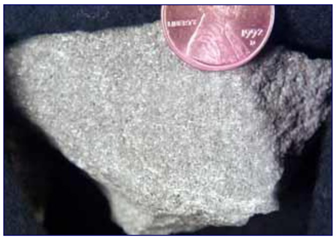






Interpreting Sandstones – *e.g.*, 4

Feldspathic “wacke” or Feldspathic muddy sst.



Possibly reflects a dissected arc

The grains are small enough and the matrix abundant enough it can be difficult to assess the amount of matrix.

Formation & Environment

Incomplete weathering, rapid transport, and rapid burial relatively close to the source. Upper Ordovician Martinsburg Fm., deposited in a submarine fan.